SECONDARY INNOVATION: THE EXPERIENCE OF CHINESE ENTERPRISES IN LEARNING, INNOVATION AND CAPABILITY BUILDING[1]

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Abstract: Nowadays enterprises have played an important role in China's economic development and increasingly become the main force of China's growing research and innovation activities. Different from some related work on developing countries' innovation policy and strategy, the evolutionary model of secondary innovation, based on Chinese enterprises' innovation practice, highlights the significant role of enterprises in systems of capability building and innovation, and opens the black box to uncover the dynamic process of enterprises' organizational learning, knowledge accumulation and capability building. Moreover, since enterprises are considered as open systems and one important job of organizational learning is to address rapidly changing environments, interactions between systems of innovation inside and outside the enterprises are also highlighted in the model. In a word, the secondary innovation model provides a useful analytical framework for better understanding the micro-level systems of learning, innovation and capability building in developing countries.

Key words: secondary innovation; organizational learning; capability building; China; case study

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1. Introduction

Nowadays enterprises have played an important role in China’s economic development and increasingly become the main force of China’s growing research and innovation activities. Different from some related work on developing countries’ innovation policy and strategy, the evolutionary model of secondary innovation, based on Chinese enterprises’ innovation practice and firstly proposed by Wu Xiaobo in early 1990s, highlights the significant role of enterprises in systems of capability building and innovation, and opens the black box to uncover the dynamic process of enterprises’ organizational learning, knowledge accumulation and capability building. As the words of Kim Linsu (1998), “models that capture organizational learning and technological change in developing countries are essential to understand the dynamic process of capability building in catching-up in such countries and to extend the theories developed in advanced countries.” Moreover, since enterprises are considered as open systems and one important job of organizational learning is to address rapidly changing environments, interactions between systems of innovation inside and outside the enterprises are also highlighted in the model. In a word, the secondary innovation model provides a useful analytical framework for better understanding the micro-level systems of learning, innovation and capability building in developing countries.

Hangzhou Hangyang Co.,Ltd. (HHCL), a leading air separation plant manufacturer in China, is a good example to illustrate the organizational learning, knowledge accumulation and capability building process of secondary innovation. On the basis of more than 10 years field study in Hangyang and other primary and secondary information sources, this paper attempts to test the existing theoretical framework of secondary innovation and explore some new thoughts and implications for further development of existing theory through in-depth case study of Hangyang.

2. Theoretical Framework of Secondary Innovation

2.1 Technology Evolution Process of Secondary Innovation

Building upon Giovanni Dosi’s notion of technological paradigm and technological trajectories, secondary innovation is defined as the specific innovation process especially in developing countries that begins with technology acquisition from developed countries and further develops along the acquired technologies’ existing trajectories within established technological paradigm, which is generated and dominated by the original innovation process.

According to the dynamics of technology acquisition and potential sources of latecomer advantage exhibited in Fig.1, which connects Foster’s S-curve framework with Abernathy and Utterback’s dynamic model of industrial innovation, two typical patterns of secondary innovation are identified: standard secondary innovation is based on the acquisition Ⅰ, and post secondary innovation is based on the acquisition Ⅱ.

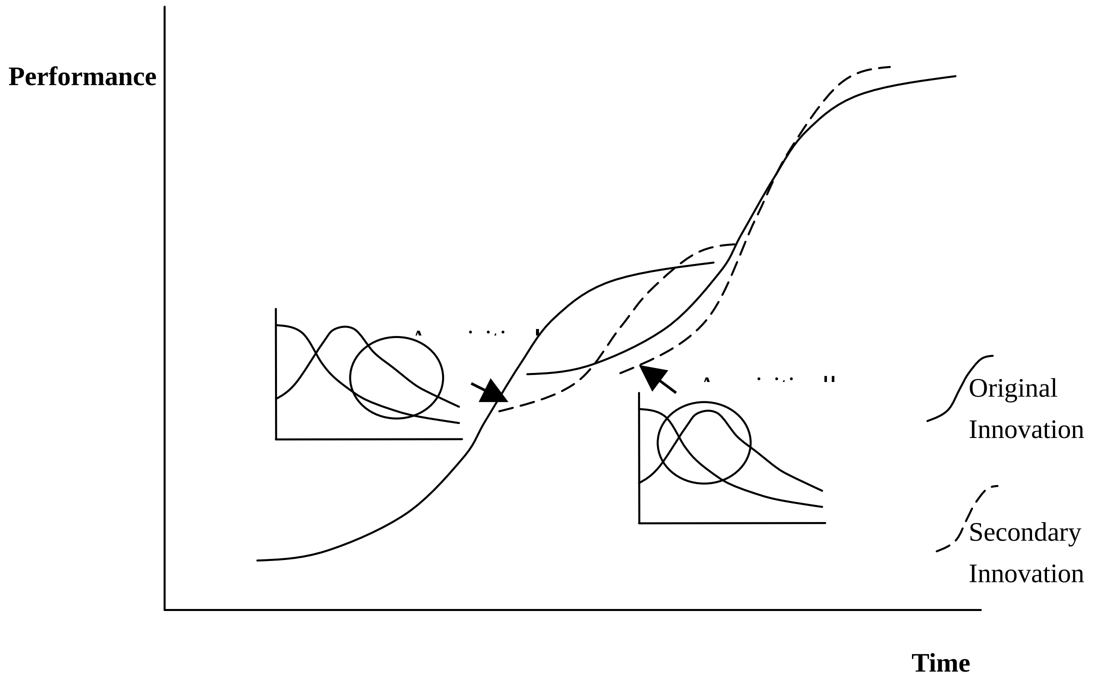

Fig.1 Technology Trajectories of Secondary Innovation

The acquisition Ⅰ, on which standard secondary innovation is based, generally selects mature technologies from developed countries. As the dominant design matures in the specific stage, latecomers in developing countries can import foreign mature technologies to reduce entry risks and R&D investments. Moreover, it is possible, but difficult, for latecomers to catch up and compete with those pioneers through their efforts in assimilation and improvement along established trajectories. It is plausible that the more mature technologies latecomers select, the more substantial latecomer advantage can be realized through secondary innovation. However, there appears to be not enough time for latecomers to exploit economic value from the incumbent technological paradigm before the new emerging technological paradigm renders the acquired technologies obsolete, and thus latecomers would lag behind again while the new dominant design matures.

Although the phenomena of technological paradigm shifts may cause latecomers fall into a vicious circle of “import - lag behind - import again”, it also opens a window of opportunity for latecomers to realize technological leapfrogging since pioneers may be path-dependency and over-consolidate investments within established technological paradigm. Different from the acquisitionⅠ, the acquisition Ⅱ as the basis of post secondary innovation usually selects emerging technologies in developed countries, which are still in the transitional stage. Importing foreign emerging technologies is a good way to evolve into original innovation through in-house R&D in the early stage of technology development. Although post secondary innovation requires high-level R&D capability and advanced production capability and can be thought as a higher level form of standard secondary innovation, it is also on the basis of acquired technologies and still cannot generate and develop a new technological paradigm.

2.2 Capability Building Process of Secondary Innovation

Kim (1997) offered new insights into the evolution of technological capabilities and illustrated the capability building process from duplicative imitation to creative imitation and innovation in developing countries. In his definition, technological capability refers to the ability of an organization to “make effective use of technological knowledge in efforts to assimilate, use, adapt, and change existing technologies” or the ability to “create new technologies and develop new products and processes in response to changing economic environment”.

Kim (1998) proposed that the term “technological capability” is often used interchangeably with the term “absorptive capacity”, which was firstly proposed by Cohen and Levinthal and defined as the firm’s ability to value, assimilate, and apply new knowledge. In the view of Kim, absorptive capacity, as a combination of effort and knowledge bases, requires learning capability and develops problem-solving skills. In Zahra and George (2002), they suggested a reconceptualization of absorptive capacity as a dynamic capability pertaining to knowledge creation and utilization that enhances a firm’s ability to gain and sustain a competitive advantage and identified four dimensions of absorptive capacity: acquisition, assimilation, transformation, and exploitation.

In this paper we use the pattern and orientation of problem-solving to classify the dimensions of an organization’s technological capability. According to Kim (1998), learning capability is the capacity to assimilate knowledge (for imitation), whereas problem-solving skills represent a capacity to create new knowledge (for innovation). In short, imitation is a problem-solving process of knowledge utilization, while innovation is a problem-solving process of knowledge creation. According to March’s classification, exploitation includes such things as “refinement, choice, production, efficiency, selection, implementation, execution”; exploration includes such things as “search, variation, risk taking, experimentation, play, flexibility, discovery, innovation”. In other words, exploitation highlights refinement and extension of existing competencies within established conception framework, while exploration highlights experimentation with emerging ideas and concepts.

As shown in Fig.2, four distinct and complementary dimensions of an organization’s technological capability are classified: duplicative imitation, creative imitation, exploitative innovation and explorative innovation. Different from Kim’s classification (duplicative imitation, creative imitation and innovation), this conceptual model highlights the difference between exploitative innovation and explorative innovation, which reveals the increasing requirement of organizational responsiveness to the rapidly changing environment (Teece et al., 1997). The capability building process of secondary innovation shown in Fig.3 illustrates the latecomer’s knowledge creation and accumulation process based on the interaction and integration of external acquisition and internal generation.

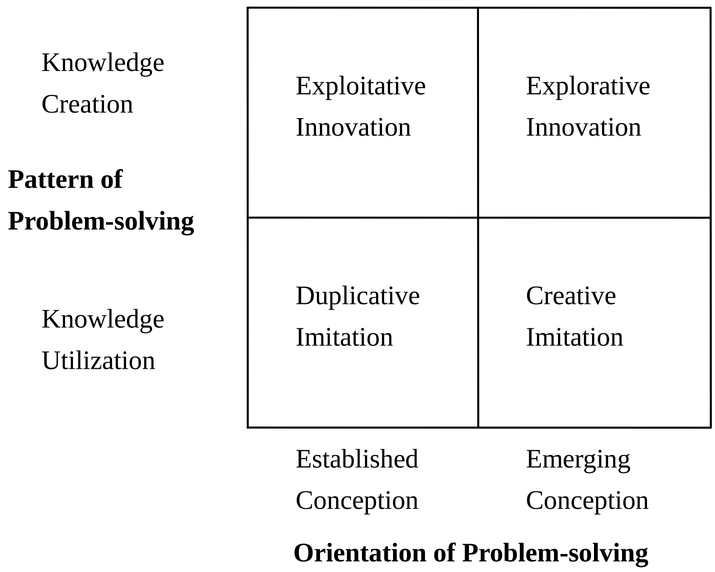

Fig.2 Taxonomy of Technological Capabilities

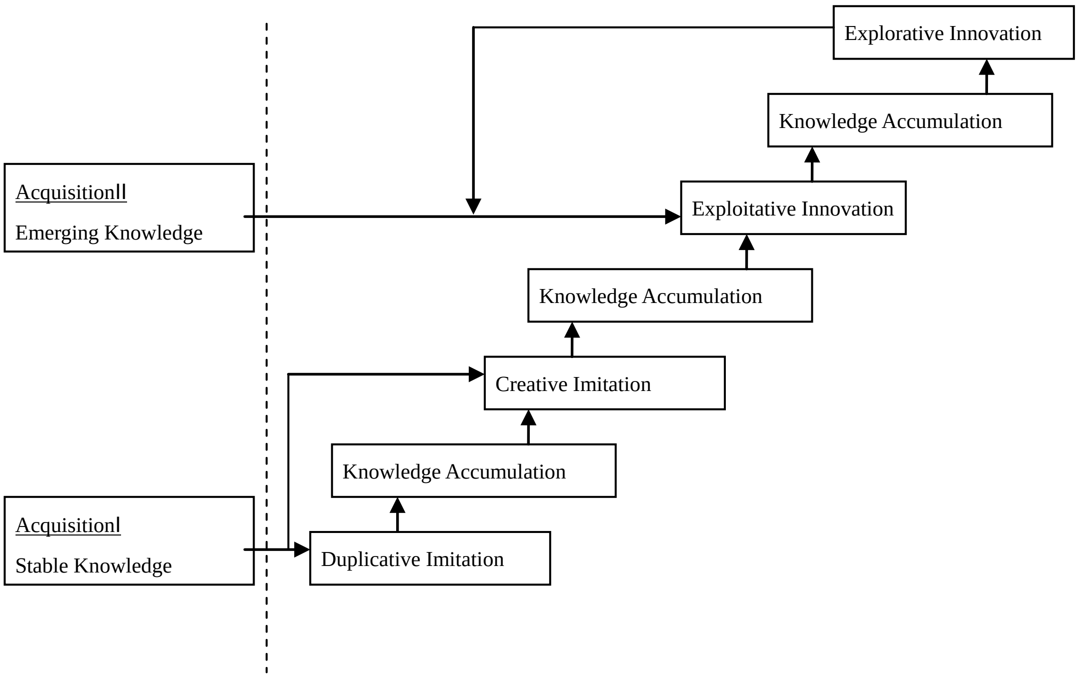

Fig.3 Capability Building Process of Secondary Innovation

2.3 A Typical Cycle of Secondary Innovation

"Stages are really only an intellectual tool simplifying a complex process" (NSF, 1983). A typical cycle of secondary innovation can be divided into five specific stages: acquisition, assimilation, improvement, crisis and renewal. Those stages are not independent and may be overlapped. Correspondingly, there are five different modes of organizational learning varying from simple to complex, and linear to non-linear: adaptive learning, maintenance learning, developmental learning, transitional learning and creative learning (shown in Fig.4). Although this classification of organizational learning modes are inspired by Meyers's four types of organizational learning, the exact meaning of each mode and underlying relationships between those learning modes are rather, to some extent, different from Meyers's original definitions and main points since Meyers's work is based on original innovation process.

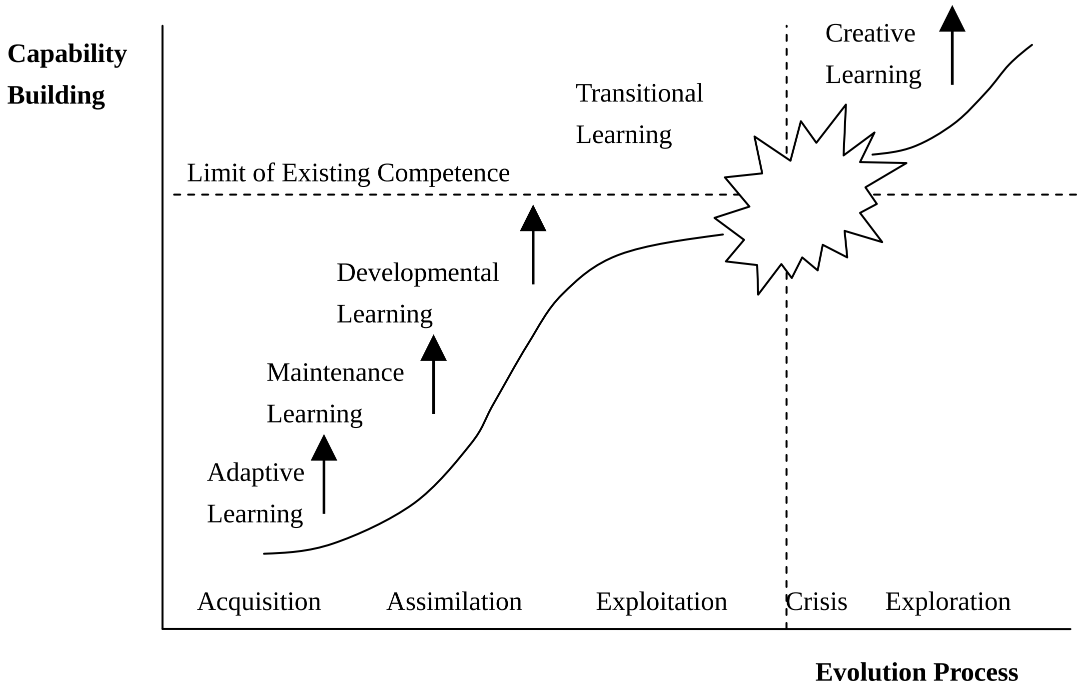

Fig.4 Organizational Learning Process of Secondary Innovation

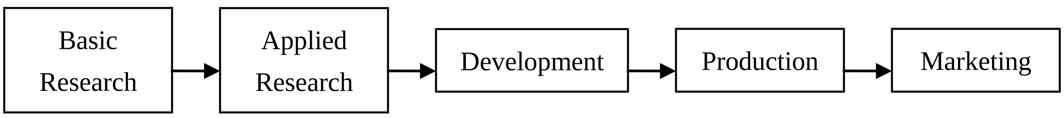

Fig.5 Original Innovation Process

A literature review of Garcia and Calantone (2002) revealed that the OECD (1991) definition on technological innovations best captures the essence of innovations from an overall perspective, “Innovation is an iterative process initiated by the perception of a new market and/or new service opportunity for a technology-based invention which leads to development, production, and marketing tasks striving for the commercial success of the invention.” According to this definition, a technology-based invention is the start of innovation process and the main task of innovation is to commercialize the invention (See Fig. 5).

It should be noticed that the so called “secondary innovation” is not a specific kind of innovation, and is rather a set of innovations. Since secondary innovation is an accumulative evolutionary process, it is difficult to use only one form to characterize different kinds of secondary innovation in different stages. Here four typical forms of secondary innovation are identified and each process corresponds to a specific technological capability level mentioned and defined above: duplicative imitation, creative imitation, exploitative innovation and explorative innovation.

As shown in Fig.6, technology acquisition is the start of secondary innovation process and the most important thing in this stage is to master the operation technology. Through importing technical know-how, blueprints, equipments, production manuals and technicians, production capability is formed and functional performance is achieved through learning by doing (Rogers, 1962). Adaptive learning is the dominant organizational learning mode of this stage and the main task is to adjust to the new technological paradigm.

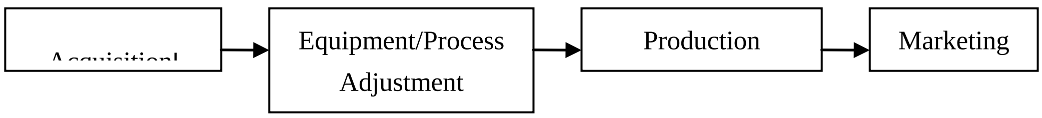

Fig.6 Secondary Innovation Process Ⅰ(Duplicative Imitation)

The localization process of acquired technologies is named assimilation, and "structural understanding", which refers to the interaction between the acquired technologies and existing technologies, is very useful and powerful in this stage (See Fig.7). Learning by using (Rosenberg, 1982) played a significant role in the localization process. Maintenance learning becomes the dominant organizational learning mode of this stage and the main object is to make the production systems more reliable and more efficient.

Fig.7 Secondary Innovation Process Ⅱ(Creative Imitation)

Entering the improvement stage, high-level design capability is formed and the acquired technologies are combined with existing ones and applied to different fields, which is named "functional learning". Developmental learning becomes the dominant organizational learning mode of this stage and the main task is product improvement, diversification and innovation within established technological paradigm (See Fig.8). The pull force from the demand side such as user requirements played a significant role in this process. The dependency on foreign technologies greatly decreased and a lot of incremental innovations are made by new combinations and new applications.

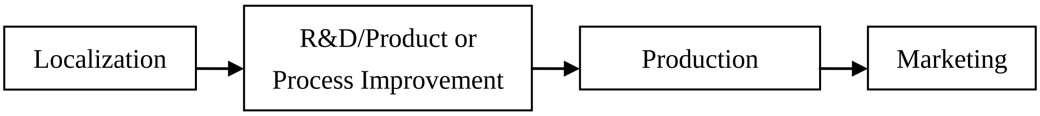

Fig.8 Secondary Innovation Process Ⅲ (Exploitative Innovation)

Although latecomers have mastered the acquired technologies and accumulated necessary knowledge and capacities through the acquisition, assimilation and improvement stages, they might fall into crisis and chaos if they adhere to existing norms and past experience in a close system, which would accelerate the depreciation of organizational knowledge and close the “windows of order”. They might face the challenge of new technological paradigm, new user demand or new rivals/substitutes and the risk of falling into a vicious circle of “import - lag behind -import again”. Transitional learning becomes the dominant organizational learning mode of this stage and the main task is to address the radically changing environment and explore new technological paradigm through strategic renewal.

The renewal stage begins with new technology acquisition or in-house R&D breakthrough and initiates the next secondary innovation cycle (See Fig.9). Creative learning becomes the dominant organizational learning mode of this stage and is characterized with system restructuring and rebuilding.

Fig.9 Secondary Innovation Process Ⅳ(Explorative Innovation)

Tab.1 Stage Characteristics of a Typical Secondary Innovation Cycle

	Acquisition	**Assimilation**	**Improvement**	**Crisis**	**Renewal**
Main Objects	Adopt an established technological paradigm	Build a reliable and efficient production system	Develop new applications for different fields	Response to environmental changes	Explore an emerging technological paradigm
Major Activities	Production	Domesticalization	Exploitative R&D	Experimentation	Explorative R&D
Capability Levels	Duplicative imitation	Creative imitation	Exploitative innovation	Redefinition	Explorative innovation
Strategic Emphases	Operation capability	Design (localization) capability	Product improvement/ diversification capability	Organizational reconfiguration capability	New product conception capability

Technological Learning Mode	Learning by doing	Learning by using (Structural understanding)	Learning by development (Functional understanding)	Unlearning (Learning how to learn)	Learning by research
Organizational Learning Mode	Adaptive learning	Maintenance learning	Developmental learning	Transitional learning	Creative learning

3. Capability Building Process of Hangyang's Secondary Innovation

Hangzhou Hangyang Co.,Ltd. (HHCL), established in 1950, is a China's leading air separation plant manufacturer after the world-famous France's Air Liquide, Germany's Linde and America's APCI. As shown in Tab.2, Hangyang has attained the design and manufacture capability of series air separation plants, especially after acquiring the technology for 10000m^3/h air separation plants from Linde in 1978. In the following part, the capability building process of Hangyang will be illustrated and analyzed from technology evolution and market dynamics dimensions. As shown in Fig.10, the technological gap with international pioneers has been bridged from nearly 20 years in 1950s to nearly 10 years in 1980s and only a few years in 1990s.

Tab.2 Milestones in Hangyang's Capability Building Process

Year	Milestones
1955	Development of 30m^3/h air separation plant
1957	Foundation of China's first air separation plant production base
	Development of China's first 50 m^3/h air separation plant
1958	Development of China's first 3350m^3/h air separation plant
1968	Development of 6000m^3/h air separation plant
1982	Development of China's first 11000 m^3/h air separation plant with reversing heat exchanger process (3rd generation technology)
	Development of China's first 6000m^3/h air separation plant with normal temperature molecular sieve adsorption process (4th generation technology)
1988	Development of China's first 6000m^3/h air separation plant with normal temperature molecular sieve adsorption and boosting expansion process (5th generation technology)
	Development of China's first air separation plant with digital control system (DCS)

1992	Development of China's first 14000m^3/h air separation plant (start-up in 1993)
1996	Development of China's first 6000m^3/h air separation plant with regular packing and full rectification argon recovery process (6th generation technology)
2000	Development of China's first 20000m^3/h air separation plant (start-up in 2002)
2001	Development of China's first 30000m^3/h air separation plant (start-up in December 2002)
2003	Development of China's first 52000m^3/h air separation plant (start-up in June 2004)
2003	Development of China's first 48200m^3/h air separation plant with internal compression process (7th generation technology) (start-up in June 2004)

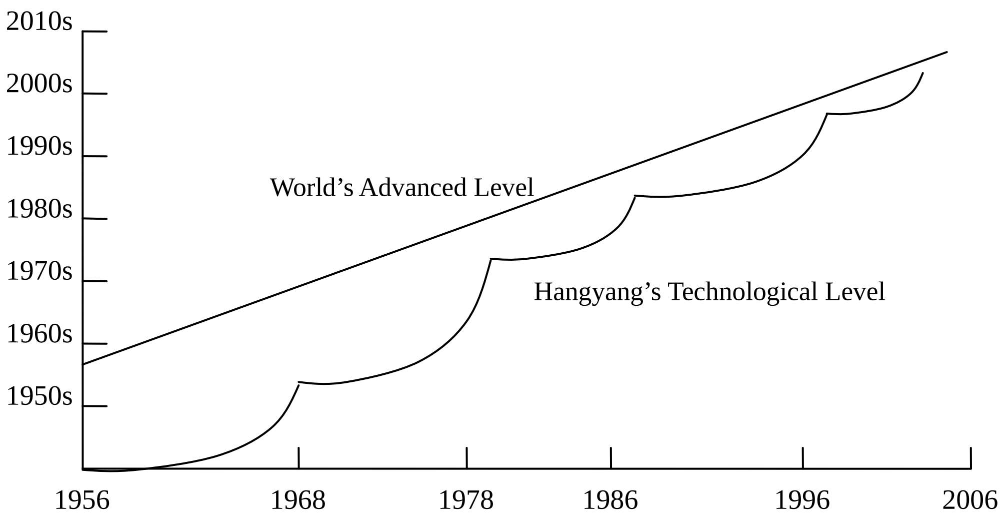

Fig.10 Hangyang's Technological Catch-up Process

3.1 Technology Evolution

As Henderson and Clark (1990)'s points that "traditional categorization of innovation as either incremental or radical is incomplete and potentially misleading", the evolutionary process of Hangyang's technological capability is sketched in Fig.11 attaching enough attention to modular innovation and architectural innovation. The on-going emergence of modular innovations, such as expansion turbine, plate-fin heat exchanger, molecular sieve, boosting expander, structured column and liquid oxygen pump, has already triggered seven revolutions of dominant air separation plant design from high-low pressure process with aluminum-plate regenerators (the 1st generation dominant design), to low pressure process with stone-filled regenerators (the 2nd generation dominant design), to low pressure process with reversing heat exchangers (the 3rd generation dominant design), to normal temperature molecular sieve purification process (the 4^{th} generation dominant design), to normal temperature molecular sieve purification process with boosting expander (the 5^{th} generation dominant design), to structured packing process with full rectification argon recovery (the 6^{th} generation dominant design), and to large-scale internal compression process (the 7^{th} generation dominant design).

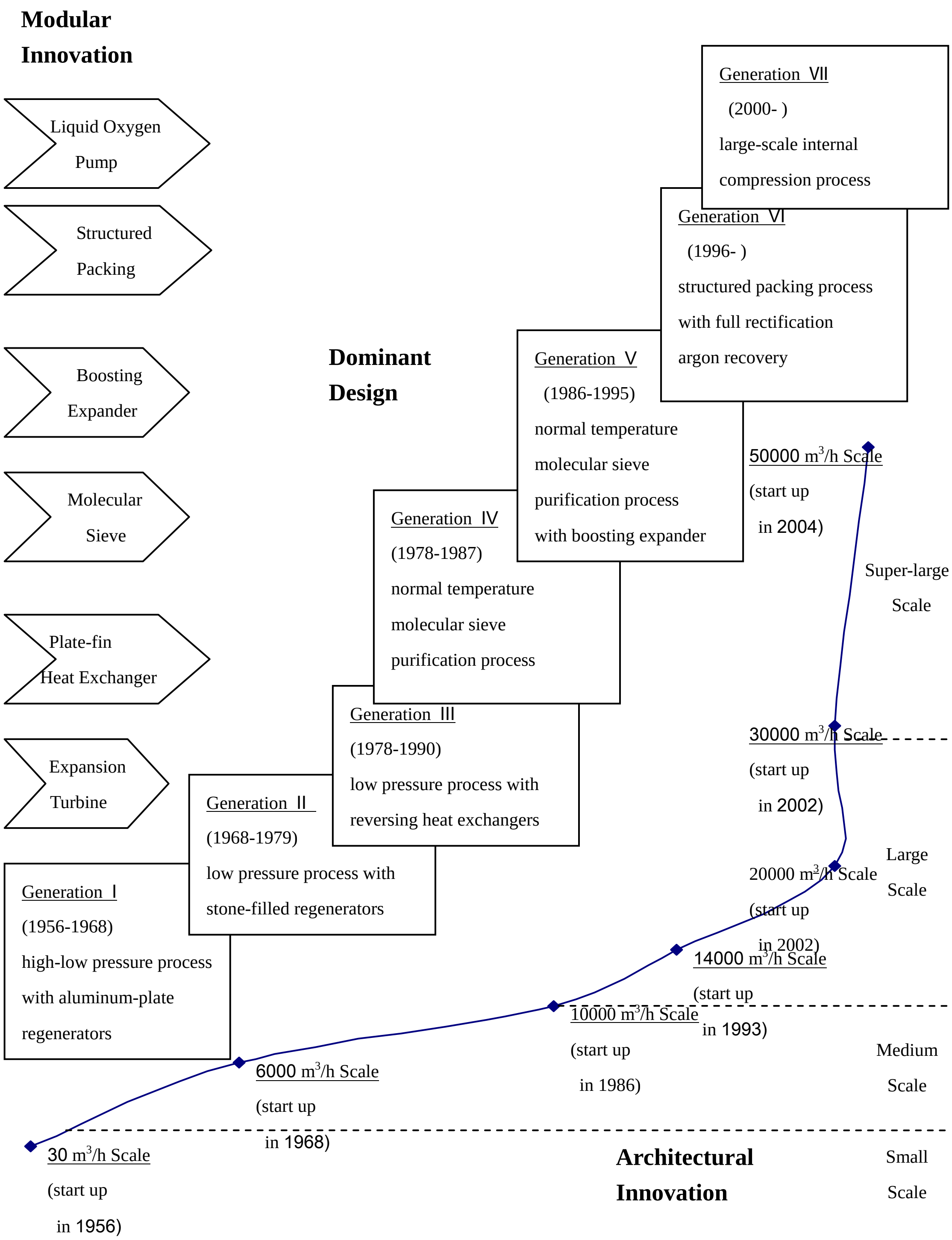

Fig.11 Hangyang's Technological Evolution Process

Concurrently, Hangyang also experienced the architectural evolution from 30m^3/h to 6000m^3/h, to 10000m^3/h, to 14000m^3/h, to 20000m^3/h, to 30000m^3/h, to 50000m^3/h scale air separation plant. Although an architectural innovation does not change the core concepts of an existing dominant design, a large air separation plant is not a simple amplification of a small one since it requires considerable changes in linkages between components and core concepts.

3.2 Market Dynamics

Sales order is a good indicator to exhibit the market performance of Hangyang's air separation plants, which is closely related to the technology evolution process in both radical innovation and architectural innovation dimensions since air separation plant is highly technology-intensive. In Fig.12, the progress of air separation plant is indicated by the plant scale, which is generally measured by the capacity of oxygen output. In Fig.13 and Fig.14, different generation technologies are distinguished to exhibit the evolution process of dominant designs.

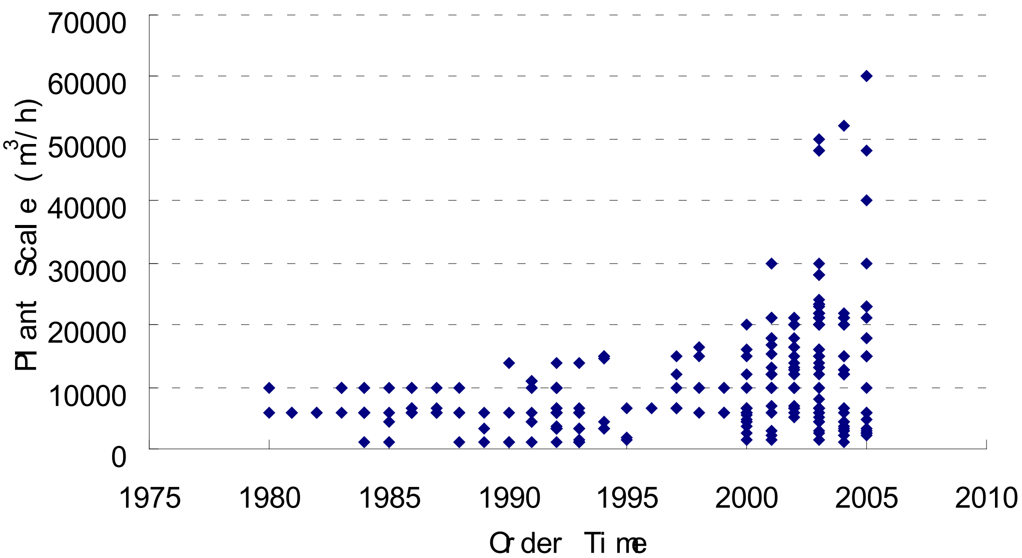

Fig.12 Market Performance of Hangyang's Air Separation Plants (1978-2005)

Besides the influences from technology side, the market dynamics of competitive environment, especially the cooperation and competition relationship with world industry leaders, also show significant impact on Hangyang's market performance and technological performance. Germany's Linde and France's Air Liquide, both of which have large investment and business in the booming China market, are the most important competitor and cooperative partner of Hangyang.

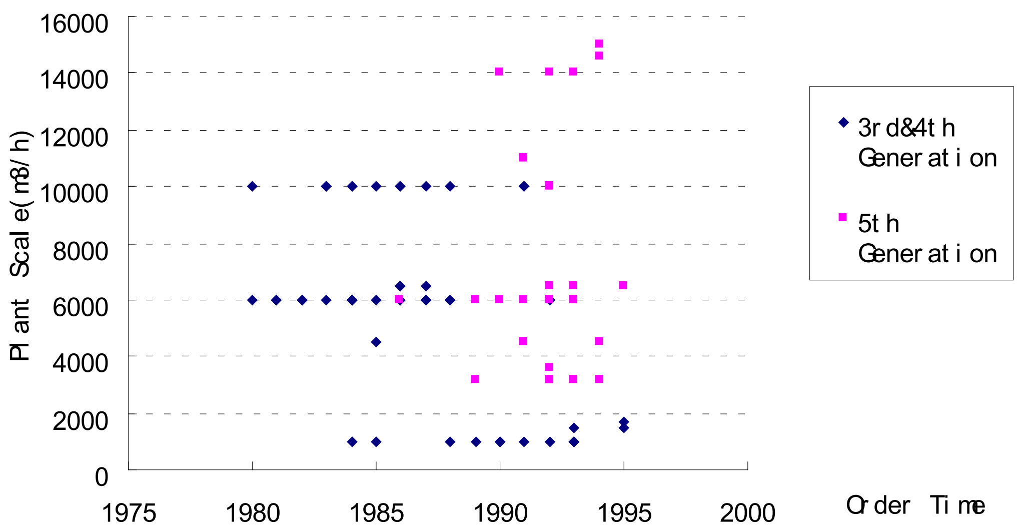

Fig.13 Market Performance of Hangyang's Air Separation Plants (1978-1995)

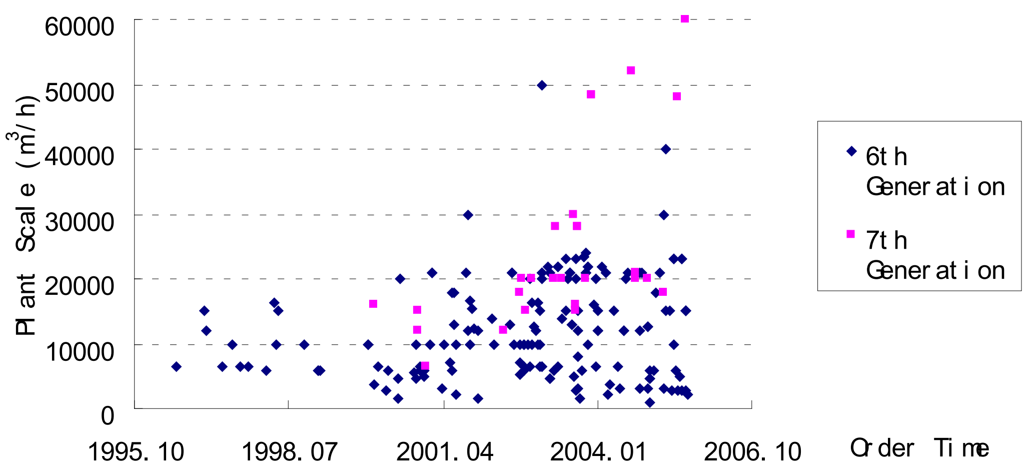

Fig.14 Market Performance of Hangyang's Air Separation Plants (1996-2005)

Since 1978 when Hangyang and Linde signed the technology and trade combination contract, the longstanding relationship between Hangyang as China's market leader and Linde as world's market leader has experienced three periods: technology transfer, project collaboration and direct competition. Recently Hangyang and Linde began direct competition in some international bidding projects. Some critical events in Hangyang and Linde's cooperation process are shown in Tab.3.

Tab.3 Critical Events in Hangyang and Linde's Cooperation Process

Year	Critical Events
1978	Imported the know-how for 10000m^3/h air separation plant design and manufacture from Linde
1979	Transferred the fin-processing know-how and equipment for plate-fin heat exchanger to Linde
1980	Participated in Linde's 10000m^3/h and 28000m^3/h air separation plant cooperative production
1986	Imported the know-how for Digital Control System (DCS) for 10000m^3/h air separation plant from Linde
1987	Participated in Linde's 30000m^3/h air separation plant cooperative production
1988	Imported the advanced Pressure Swing Adsorption (PSA) technology from Linde
1994	Participated in Linde's 25500m^3/h, 21400m^3/h, 12000m^3/h air separation plant cooperative production

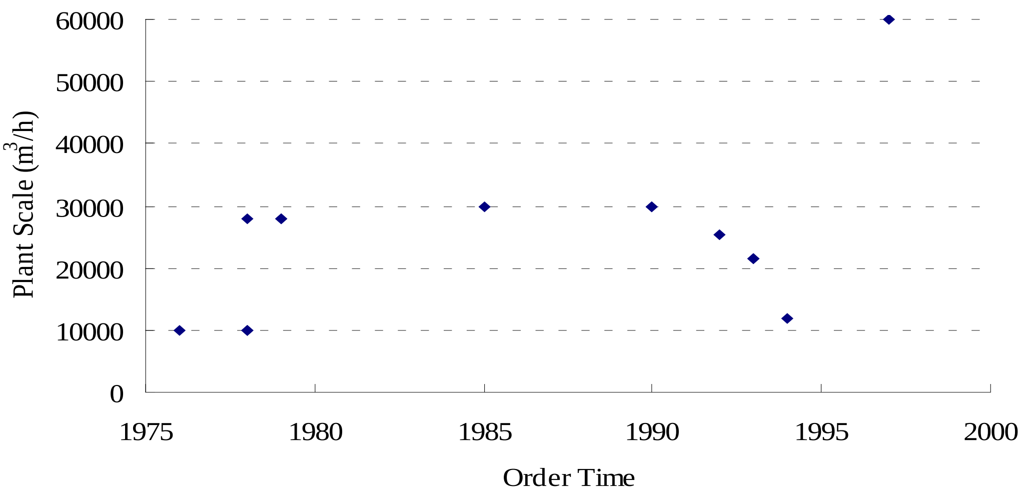

Fig.15 Hangyang and Linde's Cooperative Production Projects (1976-1998)

As shown in Fig.15, between late 1970s to late 1990s, Hangyang and Linde had already conducted 16 cooperative production projects of air separation plants ranged from 10000 m^3/h scale to 60000 m^3/h scale. The main content of their longstanding cooperation included manufacturing of coldbox, molecular sieve absorber and so on.

Besides the cooperation with Linde, from 1996 to 2001, Hangyang and its joint-venture with France's Air Liquide (Hang Yang Air Liquide Co., Ltd.) cooperatively manufactured a 28000 m^3/h air separation plant for Huainan project, a 18000 m^3/h air separation plant for Jinshan project and a 20000 m^3/h air separation plant for Benxi Steel project, in the form of providing turbo-expander, main heat exchanger, main condenser, argon condenser and other components.

Since 1998 when Hangyang gained the first order to provide a 10000 m^3/h air separation plant for world's leading industrial gases company Germany's Messer, Hangyang gradually enhanced its cooperative relationship with strategic complementors such as Messer and other industrial gases companies. Messer now specializes in industrial gases supply and does not involve in air separation plant manufacturing activities, although Messer owns longstanding know-how for air separation plant operation and manufacture. In 2004, Hangyang and Messer signed a comprehensive agreement about the joint promotion and development of both companies. In 2006, Hangyang and Messer signed a joint-venture agreement to establish a new company Cryogenic Engineering GmbH, which will be responsible for the completion of turn-key projects and marketing the facility targeting at the booming markets in Europe and the Near/MiddleEast. Hangyang holds the majority equity ownership of the joint venture based in Germany.

Besides strong foreign competitors, Hangyang also faces growing competition pressure from domestic rivals such as Sichuan Air Separation Plant Co.,Ltd. and Kaifeng Air Separation Plant Co.,Ltd., although Hangyang holds a leading position in China and occupied nearly 70% share in domestic large air separation plant market.

4. Organizational Learning Process of Hangyang's Secondary Innovation

Corresponding to the capability building process of Hangyang's secondary process analyzed above from technology evolution and market dynamics dimensions, the following analyses will uncover the underlying organizational learning process to explain why Hangyang can accumulate its organizational capability step by step in response to the increasing technological and market competition. In Tab.4 three typical secondary innovation cycles are identified as CycleⅠ (1978-1985), CycleⅡ(1986-1995), Cycle Ⅲ(1996-).

Tab.4 Hangyang's Secondary Innovation Process (1978-)

	Cycle Ⅰ	**Cycle Ⅱ**	**Cycle Ⅲ**
Period	1978-1985	1986-1995	1996-
Dominant Design	3rd&4th generation	5th generation	6th &7th generation
Architectural Knowledge	6000-10000 m^3/h	10000-15000 m^3/h	20000-60000 m^3/h
Capability Level	Duplicative imitation	Creative imitation	Exploitative innovation
Subject System	Gradually open	Nearly open	Wholly open
Technology Acquisition	Packaged import	Unpackaged import	Technical collaboration
Collaboration with Foreign Partners	Technology transfer	Project collaboration	Strategic partnership

During the period 1978-1985, based on the packaged technology import including know-how and equipment from Linde and the considerable training of operational, technical and managerial personnel provided by Linde according to the technology and trade combination contact signed in 1978, Hangyang gradually assimilated and mastered the production technology of 3rd and 4th generation air separation plants and developed 1000 m^3/h, 6000 m^3/h and 10000 m^3/h air separation plants.

During the period 1986-1995, on the base of technology acquisition and self development, Hangyang mastered five key technologies for 5th generation air separation plant, developed China's first 6000 m^3/h 5th generation air separation plant for Jilin Chemical in 1986-1988, and then applied the 5th generation to 3200 m^3/h - 15000 m^3/h scale product series.

Tab.5 Hangyang's Organizational Learning Process (1978-)

Stage	Learning Mode	Critical Events
Acquisition 1978-1980	Adaptive learning	Imported Linde's packaged know-how and equipment for the 3rd and 4th generation air separation plants and manufactured products with 8% localization content
Assimilation 1981-1982	Maintenance learning	Manufactured the 3rd and 4th generation products with 80% localization content
Improvement 1983-1984	Developmental learning	Manufactured products with 92% localization content and diversified product lines for specific use
Crisis 1985-1986	Transitional learning	Domestic clients began to import foreign 5th generation air separation plants.
Renewal/ Acquisition 1986-1988	Creative learning	Self developed five new core technologies for the 5th generation air separation plant on the base of informal unpackaged import
Assimilation 1989-1990	Maintenance learning	The 5th generation air separation plant reached world's mid-1980s advanced level.
Improvement 1991-1993	Developmental learning	Developed 14000m^3/h air separation plant Exported the first air separation plant to India
Crisis 1994-1995	Transitional learning	Foreign competitors increased investment in China and intensified the domestic market competition
Renewal/ Acquisition 1996-1998	Creative learning	Self developed new core technologies for the 6th generation air separation plant through collaboration with foreign pioneers
Assimilation 1999-2002	Maintenance learning	Successful domesticalization of super large air separation plant with 6th generation technology
Improvement 2003-	Developmental learning	Developed specific super large air separation plants for petroleum and chemical industry with 7th generation technology

4.1 Transitional Learning in the Crisis Stage between Cycle Ⅱ and Cycle Ⅲ

Since early 1990s, foreign leading air separation plant manufacturers like Linde began to think Hangyang as their potential rivals and take measures to check the growth of Hangyang. Thus, Hangyang was no longer able to get technological know-how formally from those foreign pioneers and had to try new manners to access foreign advanced technologies. In 1994, Hangyang and France's Air Liquide established a joint-venture Hangyang Air Liquide Co., Ltd, in which foreign partner held the majority equity ownership. However, Hangyang's attempts to access advanced technology through joint venture gained trivial returns and core technologies in the joint-venture were wholly controlled by the foreign partner.

Moreover, direct investment of those foreign air separation plant manufacturers in China during middle 1990s largely enhanced Hangyang's competitive pressure. In 1995, Germany's Linde and China's Bingshan also established a joint-venture Linde Process Plant Co., Ltd, in which the majority shares was also held by the foreign partner. On the one hand, those joint-ventures in China not only drew some orders from Hangyang's potential clients but also attracted a number of excellent technical talents with ample local market experience from Hangyang. On the other hand, the growing business in China also forced those foreign giants to increase localized production content and actively utilize Hangyang and other local manufacturers' production capacities to largely cut down their costs. For example, both Linde and Air Liquide invited Hangyang to manufacture some components locally for their whole set projects, and those cooperative production projects provided Hangyang good opportunities to learn from foreign pioneers through direct interaction.

The development of structured packed column and full rectification process of argon recovery in 1970s and 1980s led to the prevalence of the 6th generation dominant design of air separation plant in 1990s. Since 1970s, some famous manufacturers like Switzerland's Sulzer and France's Air Liquid successively adopted structured packed column instead of plate sieve column in air separation plant design. Hangyang had already paid attention to this technical trend and made attempts to preliminarily master those two core technologies through pilot scale experiments. Before the official adoption of the structured packing technology in large and medium scale air separation plants, Hangyang had already applied the new technology to argon column in the 1500m^3/h air separation plant reconstruction project for Wuyang

Steel in 1993 and attained a considerable amount of data from the 150m^3/h air separation plant's upper column experiments during 1994-1995. In January 1996, the pilot project of China's first 1000m^3/h full rectification argon recovery unit with structured packed column for Shanghai Loutang project was commissioned successfully, which signals that China has become the 4^{th} country mastering this advanced technology after Germany, France and US.

4.2 Creative Learning in the Renewal Stage of Cycle Ⅱ(Acquisition Stage of Cycle Ⅲ)

Since July 1996, Hangyang successively gained the 6^{th} generation air separation plant orders from Hangzhou Steel, Xingtai Steel and other industrial users. On October 18, 1998 the 6000m^3/h air separation plant developed by Hangyang for Xingtai Steel started up successfully. One month later, the 12000m^3/h air separation plant developed by Hangyang for Shanghai Steel also successfully started up.

Learning by doing, in the cooperation with foreign pioneers, played a significant role in Hangyang's adoption process of the structured packing technology, which is the core content of the 6^{th} generation dominant design, for large and medium scale air separation plants. Hangyang collaborated with foreign pioneers France's Air Liquide and Switzerland's Sulzer on the design and manufacture of structured packed column, such as the Xingtai Steel project in cooperation with Air Liquid and Shanghai Steel project in cooperation with Sulzer. Hangyang also conducted cooperative design projects with domestic universities and research institutes, such as the Juhua project in cooperation with Tianjin University and Shanghai Research Institute of Chemical Industry.

It should not be neglected that it is impossible for the fast-growing Hangyang to acquire core technologies such as structured packing directly from foreign pioneers in the form of packaged import. Thus, Hangyang had to make great efforts on its own to master the new core technologies and combine the new capability with existing 5^{th} generation design capability through reverse engineering. Hangyang gradually understood the underlying principle of the 6^{th} generation technology through mapping and testing the actual machines in international cooperative projects, and then combining those observed operating data with limited available foreign literature. That is why the dominant learning mode in the acquisition process of 6th generation technology is creative learning rather than adaptive learning.

Concurrently, learning by doing, on the basis of importing foreign software and databases for system design and control and absorbing foreign experience and literature, also played an important role in the adoption process of 6th generation dominant design. Based on assimilation of foreign technology and commissioning experience, Hangyang grasped the design, calculation and control of new generation air separation process through combining its own testing and operating experience with domestic user requirements. In process calculation, for example, Hangyang developed new calculation model according to the new dominant design and continuously adjusted the model according to new operating data and foreign literature. On the basis of imported physical property database and process simulation software, Hangyang independently developed calculation software for the 6th generation air separation process to guarantee high calculation precision. Hangyang also absorbed some foreign design concepts to improve the system reliability, importing Air Liquide's basic process design and control solutions with relative calculation results and comparing with its own solutions and results to further modify and improve its calculation model.

Besides mastery of those component or architectural knowledge, Hangyang also made some incremental improvements for the 6th generation dominant design, such as the efforts for better performance of coldbox, air-cooling system and molecular sieve system.

4.3 Maintenance Learning in the Assimilation Stage of Cycle Ⅲ

The smooth start-up of China's first air separation plant with structured packed column and full rectification argon recovery process in 1998 signals Hangyang's mastery of 6th generation dominant design including both core component technologies and critical architectural improvements. Since 1998, Hangyang's 6th

generation air separation plants have gained the approval of international clients and successively gained orders from world-famous industrial gas companies like Germany's Messer and UK's BOC. In 2001, Hangyang's 6^{th} generation air separation plant was awarded First-class Prize of science and technology of Chinese mechanical industry, First-class Prize of science and technology in Zhejiang Province and First-class Prize of science and technology in Hangzhou City.

Grounded on basic technological capability of $10000m^3/h$ 6^{th} generation air separation plant, Hangyang applied the 6^{th} generation technology to architectural breakthroughs in $20000m^3/h$ and $30000m^3/h$ air separation plants. In 2000, Hangyang gained Jinan Steel's order for China's first $20000m^3/h$ air separation plant with 6^{th} generation technology, which started up in February 2002. In 2001, Hangyang undertook the domestication project of $30000m^3/h$ air separation plant with 6^{th} generation technology for Bao Steel. On December 14, 2003, this $30000m^3/h$ air separation plant successfully started up and achieved world-advanced-level overall performance, setting up a new milestone on the history of China's national air separation plant industry.

Learning by using played a significant role in the structural understanding process of applying the 6^{th} generation technology to $30000m^3/h$ air separation plant architecture. The Zhenhai's imported $28000m^3/h$ air separation plant reconstruction project in 1996 and Bao Steel's imported $30000m^3/h$ air separation plant reconstruction project in 1998 provided Hangyang valuable operating data and using experience to better understand the principle of $30000m^3/h$ architecture.

To meet new requirements of $30000m^3/h$ air separation plant architecture, Hangyang made great efforts to master both the design and calculation technology of entire system and new technologies for some core component such as large horizontal molecular sieve absorber. Hangyang had already accumulated some useful experience through collaboration with Linde in designing and manufacturing 8 sets of molecular sieve absorber for $30000m^3/h$ architecture. Besides the cooperative production with foreign partners, Hangyang collaborated with Xian Jiaotong University to develop new types of main condensation evaporator for large scale plant, some results of which were applied in the Bao Steel 30000m^3/h project and largely saved the room of coldbox and the costs of transportation.

4.4 Developmental Learning in the Improvement Stage of Cycle Ⅲ

Rapid growth of steel industry and chemical industry in recent years, especially the booming of petroleum and chemical industry, led to the increasing demand for super large air separation plant with much higher capacity. World's largest air separation plant, which was made by Air Liquide for petroleum and chemical industry use, is able to produce more than 100000m^3/h oxygen. The equipment investment and operation costs of a 50000m^3/h air separation plant are much less than two 25000m^3/h air separation plants. Although steel industry was still the main user of air separation plants, the demand for super large air separation plants from chemical industry boomed up very quickly. In 2005, ten of total 25 domestic orders for 30000m^3/h above scale air separation plants were from chemical industry.

To meet new specific user requirements in product variety, pureness and pressure of different industry applications, Hangyang developed a series of 30000m^3/h-60000m^3/h air separation plants with both external compression (6th generation technology) and internal compression (7th generation technology) process of oxygen (shown in Fig.15, Tab.5). After the successful domesticalization of 30000m^3/h 3.0MPa air separation plant for Bao Steel in December 2002, Hangyang gained the Beitai Steel's order for 52000m^3/h 3.0MPa air separation plant in January 2003 and the Weihe Chemical's order for 29500m^3/h 8.7MPa air separation plant in June 2004. In the end of 2003, Hangyang and Sinopec signed development agreements for two 48200m^3/h air separation plants with internal compression process. In May 2006, China's first 48200m^3/h air separation plant was commissioned successfully, which signals the end of China's petroleum and chemical companies' dependence on foreign imported super large air separation plants.

Hangyang began to adopt the 7th generation dominant design with internal compression process in 2000, and apply the new generation technology to super large air separation plants in very short time. However, the emerging 7th generation dominant design did not completely substituted the 6th generation dominant design, and the growing demand from steel industry still led to the technological progress of the 6th generation technology. In other words, the 7th generation technology just provided a new alternative combination to satisfy the increasing demand from petroleum and chemical industry, in which the air separation plants usually produce multiple products, including both gas and liquid states, with multiple pressure levels.

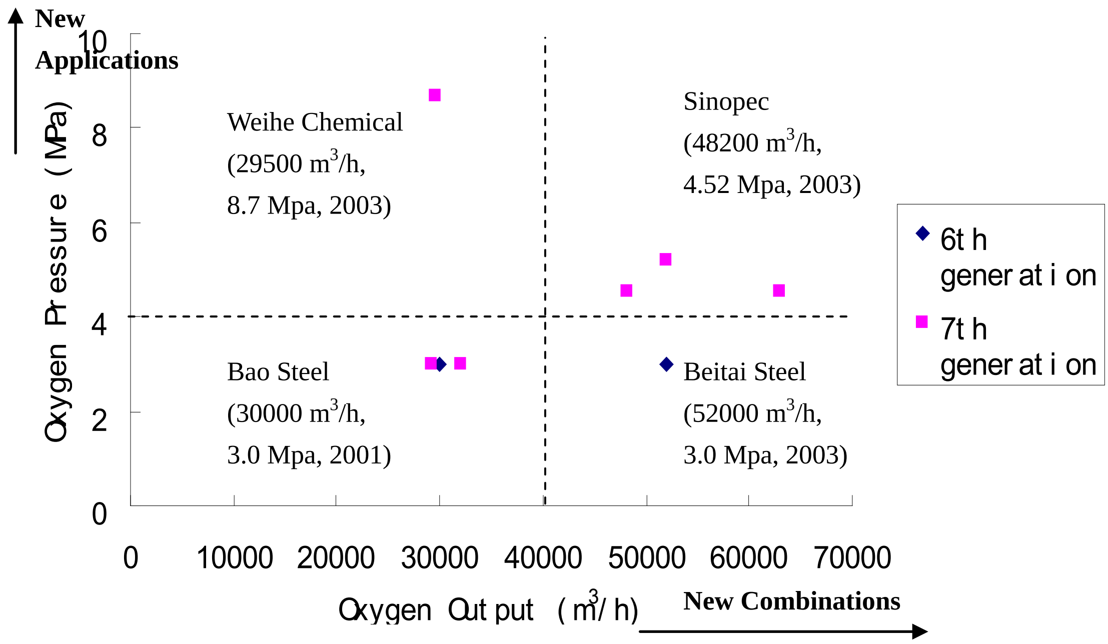

Fig.15 Improvement and Diversification of Hangyang's Air Separation Plants

User requirements from the demand side become the dominant force to promote Hangyang to utilize new market opportunities and correspondingly improve and diversify its product series through functional understanding. Generally speaking, 3.0MPa pressured air separation plant with external compression process can satisfy the requirement of steel industry, and the petroleum and chemical industry requires 4.0MPa-10.0MPa product pressure for air separation plant, for which the 7th generation internal compression process is a better choice. Besides, internal compression process is also a good alternative for steel industry if the user is in need of liquid products. Moreover, in the internal compression process for chemical industry application, the pressure of oxygen can be divided into two levels: medium level 4.5-5.2MPa and high level 6.4-9.8MPa. According to specific pressure level of oxygen and nitrogen products, Hangyang developed five different internal compression processes. In a word, user requirement, rather than technology performance, determines the decisions of whether to adopt 6th generation technology or 7th generation technology.

Tab.5 Hangyang's Super Large Air Separation Plant Sales (2003.1-2005.1)

Order Time	User	Industry	Oxygen Output	Quantity	Compression Process	Oxygen Pressure
2003-1-18	Beitai Steel	Steel	52000 m^3/h	1	External	3.0 MPa
2003-4-26	Weihe	Chemical	29500 m^3/h	1	Internal	8.7 MPa
2003-8-18	Maanshan Steel	Steel	32000 m^3/h	1	Internal	3.0MPa
2003-8-20	Bao Steel (3#)	Steel	30000 m^3/h	1	External	3.0 MPa
2003-9-15	Tianjin Steel	Steel	29300 m^3/h	2	Internal	3.0MPa
2003-12-3	Sinopec	Chemical	48200 m^3/h	2	Internal	4.52 MPa
2004-8-28	Zhongyuan	Chemical	52000 m^3/h	1	Internal	5.2 MPa
2005-1-1	Iran Kawei	Chemical	63000 m^3/h	2	Internal	4.55 MPa

Nowadays, Hangyang has already experienced the capability building process from duplicative imitation, to creative imitation and to exploitative innovation. However, it is still a long way for Hangyang to reach explorative innovation capability level. The evolution from standard secondary innovation cycle to post secondary innovation might take several organizational learning cycles, and the revolution from secondary innovation to original innovation might require much more organizational learning cycles.

5. Conclusion

Secondary innovation is not a closed linear process from imitation to assimilation and innovation, and is rather an incremental accumulative evolutionary process with both quantitative development and qualitative change, an equilibrium process from established stable technological state to new balanced state combining existing technologies and new acquired technologies, a capability building process from duplicative imitation and creative imitation to exploitative innovation and explorative innovation and a non-linear learning process from structural understanding to functional understanding.

Secondary innovation is a “learning” and “understanding” process from mastery of operation technology, to mastery of production technology and principle, to mastery of design technology and principle, and to capability of product/process improvement. Different from traditional technological learning model, secondary innovation model emphasizes the very important interrelations and interactions between the acquired technologies and local technological and market environment, which can be named “understanding”. “Learning” is a good notion to describe the mastery process of a specific technology involving imitation and some part of adaptation, but it may mislead to being confined within definitive conception of original technology. The mastery of core technologies may be the end of technological learning, but is just the first step of secondary innovation, followed by “structural understanding” and “functional understanding” combining the acquired technologies with existing technologies and further with local user requirements.

It is greatly hoped that the in-depth analyses of Chinese enterprises’ secondary innovation experience in this paper would inspire new insights in the developing countries’ micro level systems of learning, innovation and capability building.

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